The Gravity-Loading countermeasure Skinsuit (GLCS) and its effect upon aerobic exercise performance

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A B S T R A C T

The Russian Pingvin suit is employed as a countermeasure to musculoskeletal atrophy in microgravity, though its 2-stage loading regime is poorly tolerated. The Gravity-Loading Countermeasure Skinsuit (GLCS) has been devised to comfortably compress the body via incrementally increasing longitudinal elastic-fibre tensions from the shoulders to the feet. We tested whether the Mk III GLCS was a feasible adjunct to sub-maximal aerobic exercise and resulting VO_2Max predictions. Eight healthy subjects (5♂, 28 ± 6 yr) performed cycle ergometry at 75% VO_2Max (derived from an Astrand-Rhyming protocol) whilst wearing a GLCS and gym clothing (GYM). Ventilatory parameters, heart rate (H_R), core temperature (T_C), and blood lactate (B_L) were recorded along with subjective perceived exertion, thermal comfort, movement discomfort and body control. Physiological and subjective responses were compared over TIME and between GYM and GLCS (ATTIRE) with 2-way repeated measures ANOVA and Wilcoxon tests respectively. Resultant VO_2Max predictions were compared with paired *t*-tests between ATTIRE. The GLCS induced greater initial exercise ventilatory responses which stabilised by 20 min. H_R and T_C continued to rise from 5 min irrespective of ATTIRE, whereas B_L was greater in the GLCS at 20 min. Predicted $\dot{V}O_2$Max did not differ with ATTIRE, though some observed differences in H_R were noteworthy. All subjective ratings were exacerbated in the GLCS. Despite increased perception of workload and initial ventilatory augmentations, submaximal exercise performance was not impeded. Whilst predicted VO_2Max did not differ, determination of actual VO_2Max in the GLCS is warranted due to apparent modulation of the linear H_R-VO_2 relationship. The GLCS may be a feasible adjunct to exercise and potential countermeasure to unloaded-induced physiological deconditioning on Earth or in space.

1. Introduction

Typical 6 month missions to the International Space Station (ISS) are associated with significant multi-systems de-conditioning including bone demineralisation [1], muscle atrophy [2,3], cardiovascular (contributing to aerobic) de-conditioning [4,5] and spinal elongation with associated back pain [6]. Such changes during longer missions could severely impact health and functionality upon return to Earth (1Gz) or when landing in a partial Gz environment such as Mars.

Current engagement of exercise countermeasures on the ISS includes usage of equipment such as the T2 treadmill, Cycle Ergometer with Vibration Isolation and Stabilisation System (CEVIS) and Advanced Resistive Exercise Device (ARED) as part of the overall health maintenance system [7,8]. Approximately 2.5 h in duration is spent on exercise countermeasures each day, including setup, 60 min for aerobic exercise (e.g ergonometry), 40–60 min for ARED exercise, data transfer and stowage [7]. Typically, in-flight $\dot{V}O_2$Max, estimation is via extrapolation of the heart rate (H_R) response to sub-maximal upright ergometry in 1Gz prior to flight, based on the established positive linear relationship between H_R and VO_2[9].

Although more recently loss of muscle mass and strength has been attenuated within 6-month ISS missions [10,11], such protocols still do not fully protect against weightlessness-induced physiological deconditioning for all individuals, and more importantly, such countermeasure devices would not be logistically feasible for manned missions to other celestial bodies. Thus, in preparation for exploration missions to Mars (which may take three years), a newer generation of passive countermeasures are sought, that have greater efficacy but require

Fig. 1. The traditional Pengvin suit (left) and the Mk III Gravity-Loading Countermeasure SkinSuit (GLCS; right).

fewer resources (time, volume, mass, and energy) are required [12].

Recently, the Gravity-Loading Countermeasure Skinsuit (GLCS) has been developed using bi-directional elastic weave technology in an attempt to provide progressive axial loading equivalent to that on Earth when standing [14]. Whereas the Pingvin suit has a leather belt that allows for a 2-stage garment, the GLCS uses each circumferential fibre of the elastic weave as a ‘belt’ to produce numerous vertical stages. These stages gradually increase in elastic tension along the longitudinal body axis from the shoulders to the feet. In addition, the circumferential fibres act as tethers with very low circumferential tension to prevent suit slippage (Fig. 1). The GLCS has been designed to integrate with other exercise countermeasures to improve the magnitude and comfort of impact load delivery [14], and may offer other benefits such as spinal elongation amelioration. However, whether the GLCS can be worn during astronauts' daily activities, including exercise countermeasures is yet to be determined. Previous work has shown that the Mk III GLCS (Fig. 1) provides stepwise ~0.7Gz axial loading and is viable to incorporate with resistance-based exercise [15].

Thus, the aims of this study were to determine the feasibility of GLCS-wear integrated with prolonged submaximal aerobic exercise at 75% VO_2Max, as performed on the ISS. A secondary aim was to investigate resultant VO_2Max predictions based on GLCS-induced H_R responses.

2. Methods

Eight healthy subjects (5♂, 28.4 ± 5.9 yr, 182.6 ± 9.7 cm and 77.3 ± 8.3 kg) gave written informed consent to participate in the study that received approval from King's College London Ethics Committee (BDM/11/12–106). Subjects denied taking any medication or having any history of neurological, cardiorespiratory and/or psychological disorders. None of the subjects were in pain, pregnant and/or lactating, nor had consumed alcohol for 24 h and food for 2 h, prior to testing. Testing took place in a quiet, thermo-neutral (~24 °C) environment.

2.1. Experimental design

All subjects were provided with a custom-fabricated (total mass ~0.360 kg) Mk III Gravity Loading Countermeasure Skinsuit (GLCS; Costume Works Inc, Boston, Massachusetts, USA) and appropriately sized flat-soled cycling shoes. Each participant attended a suit fitting session during which 63 anthropometric circumferential measurements from the armpit to the ankle were obtained to calculate the material strain required to generate an ~1Gz regime. One month later subjects attended the laboratory once a week for three consecutive weeks; week 1 was a familiarisation session, followed by two further visits for aerobic testing in loose fitting gym (GYM) clothing and the personalised GLCS.

2.2. Familiarisation

The familiarisation session involved donning and doffing the GLCS to ensure adequate fit in addition to estimation of 75% VO_2Max via completion of a 7-min submaximal Åstrand-Rhyming test [5] on a cycle ergometer (Monark Cycle Ergometer, Ergomedic, Sweden) in loose fitting clothes, whilst heart rate (H_R) was determined via a standard 3-lead ECG (Lifepulse, HME, UK). Participants commenced cycling at 50 W (60RPM) followed by increments of 25 W every 2 min; until a steady state H_R between 130–160 bpm was observed. The Åstrand & Rhyming nomogram was then used to calculate the power output (W) required to achieve 75% VO_2Max according to the age and gender of the subject for subsequent aerobic testing (GYM and GLCS).

2.3. Experimental protocol

Following a period of 2 min rest for baseline data collection, each aerobic testing session comprised of a single 20-min cycling bout, at the pre-determined power output (75% of predicted VO_2Max); on an upright cycle ergometer (Monark, Sweden), performed in GYM and GLCS. In the GLCS, stirrups were strapped around the pedals to apply the available loading via the soles of the cycling shoes. During cycling, H_R (BPM), expiratory flow (through a secured oro-nasal mask with Hans Rudolph pneumotachography, USA), and expired gas concentrations (AD Instruments Respiratory Gas Analyser, Australia) were continuously recorded. Core temperature ($T_{C;\ °C}$) recordings were obtained by ingestion (30 min prior to testing) of a telemetric pill (CorTemp, HQinc, USA) and finger prick blood lactate (B_L) concentration (mmol L^{-1}; SuperGL, Dr Muller, Germany) at baseline (after 3 min of rest) and at 5 min intervals during exercise. Subjective ratings of perceived exertion (RPE [16]), thermal comfort (ASHRAE Thermal Comfort and Adaptive 7-point scale [17]), body control (Modified Cooper-Harper scale [18]) and movement discomfort (Modified Corlett and Bishop scale [19]) were also collected at REST, and every 5 min during exercise.

2.4. Data analysis

Physiological data was sampled at 1 kHz (Powerlab ADC, LabChart 7.1, AD Instruments, Australia) with breath-by-breath data extracted to yield 1 min means (± SEM) for minute ventilation (V_E; L.min; BTPS), mass corrected oxygen consumption (VO_2; ml.kg.min^{-1}; STPD) and carbon dioxide production (VCO_2; L.min; BTPS), in addition to T_C and H_R. All physiological parameters were compared over TIME – from rest to 5 min, and 5–20 min - and between ATTIRE (GYM and GLCS) across these time points via two-way repeated measures ANOVA. Bonferroni corrected *post-hoc* paired *t*-tests were used to identify where significance lay in the instance that TIME, ATTIRE, and TIME*ATTIRE interaction effects were present. Estimated VO_2Max – calculated using the mean H_R from the final min of each exercise bout via the Astrand & Rhyming nomogram method – were compared between GYM and GLCS via paired *t*-tests. Subjective measurements were also compared as per the physiological parameters, albeit with (non-parametric) wilcoxon tests. Statistics were performed using SPSS (19.0, SPSS Inc., Chicago, IL, USA) with significance defined as $p <$ 0.05.

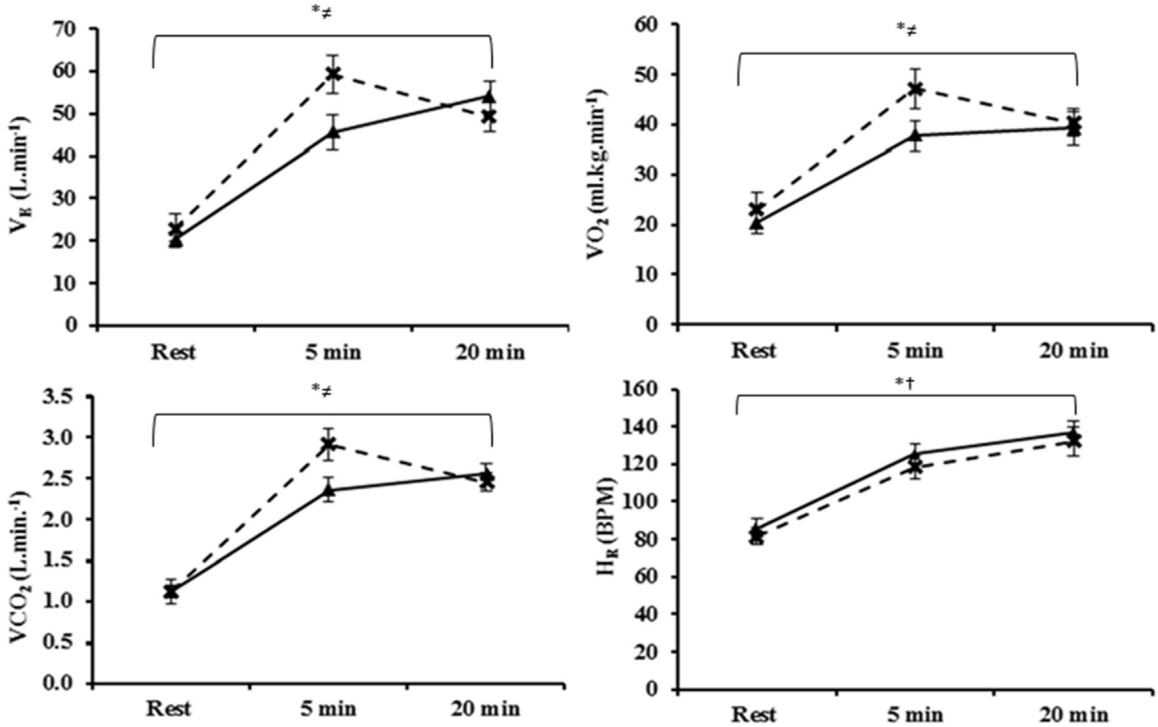

Fig. 2. A–D Clockwise from top left: Mean (± SEM) V_E (L.min^{-1}), VO_2 (ml.kg.min^{-1}), H_R (BPM) & VCO_2 (L.min^{-1}) at rest, 5 and 20 min during GYM and GLCS. *= significant effect of TIME in GYM & GLCS ($p < 0.05$). ≠= significant TIME*ATTIRE interactions for V_E, VO_2 & VCO_2 ($p < 0.05$). † = continual H_R rise post-5 min in both GYM & GLCS ($p < 0.05$).

3. Results

All subjects were able to perform at the workload determined in the familiarisation session during subsequent GYM and GLCS testing.

3.1. Physiological variables

V_E [F(2,14)=127.069; p < 0.001](Fig. 2A), VO_2 [F(2,14)=33.441; p < 0.001](Fig. 2B), VCO_2 [F(2,14)=174.490; p < 0.001](Fig. 2C), H_R [F(2,14)=98.348; $p < 0.001$](Fig. 2D), B_L [F(2,14)=22.965; p < 0.001] (Fig. 3) and T_C [F(2,14)=22.741; $p < 0.001$](Fig. 4) all increased with TIME from rest to 20 min. However, no significant increments were noted from 5 to 20 min in either GYM or GLCS except for H_R, Tc & B_L. Significant increases were noted in H_R and Tc from 5 to 20 min in GYM (p=0.024 & p=0.006 respectively) and GLCS (p=0.003 & p=0.006 respectively)(Fig. 2D & Fig. 4). B_L continued to rise from 5 to 20 min in GLCS only (p=0.022).

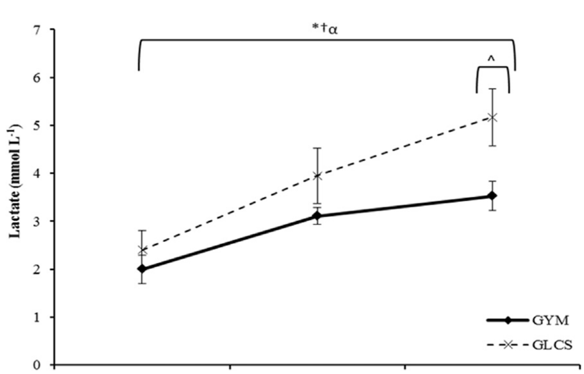

Fig. 3. Mean (± SEM) blood lactate (mmol L^{-1}) at rest, 5 & 20 min in GYM and GLCS. *= significant effect of TIME in GYM and GLCS ($p < 0.05$); † = significant effect of ATTIRE ($p < 0.05$); α= significant TIME*ATTIRE interaction; ^ = significant increase in blood lactate in GLCS vs. GYM at 20 min (p=0.009).

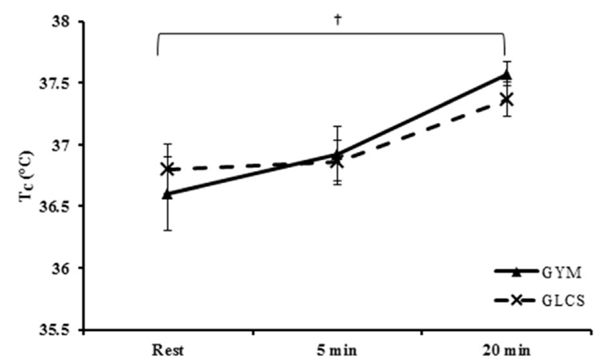

Fig. 4. Mean (± SEM) T_C (°C) at rest, 5 and 20 min in GYM & GLCS. *= significant effect of TIME in GYM and GLCS ($p < 0.05$). † = continual T_C rise post-5 min in both GYM & GLCS ($p < 0.05$).

B_L was the only parameter to differ according to ATTIRE [F(1,7) =6.692; p=0.036] with greater levels observed in the GLCS at 20 min (*P=0.009*).

Time*attire interactions were observed for V_E [F(2,14) =8.564; p=0.004], VO_2 [F(2,14) =4.127; p=0.039] and VCO_2 [F(2,14) =4.127; p=0.010]. Greater initial ventilatory responses were evident in the GLCS – as manifest by steeper slopes from rest to 5 min - but did not differ from GYM at 20 min (Fig. 2A-C). Furthermore, a TIME*ATTIRE interaction [F(1,7) =17.612; p < 0.05] was evident with B_L, owing to the continual rise in the GLCS (p=0.022), contrasted to the plateau seen with GYM (Fig. 3).

Mean predicted VO_2Max showed a tendency to be higher in the GLCS than GYM, albeit non-significantly (Fig. 5).

3.2. Subjective variables

All subjective ratings increased from rest to 5 min ($p < 0.05$; Table 1), in both GYM and GLCS. Further increments from 5 to 20 min were observed in RPE in both GYM and GLCS (0.017 & p=0.017 respectively), and in thermal and movement discomfort albeit

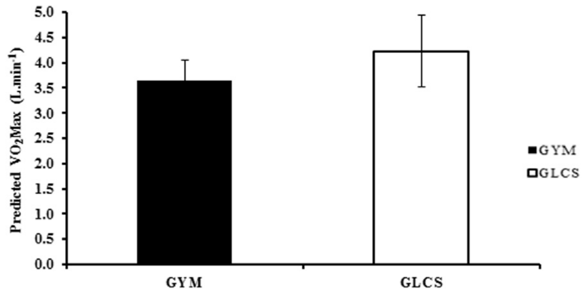

Fig. 5. Mean (± SEM) predicted VO_2Max (ml.kg.min^{-1}) in GYM and GLCS, calculated by using the mean H_R from the final min of each exercise bout within the Astrand-Rhyming VO_2Max prediction method. No significant differences in predicted VO_2Max between GYM and GLCS were present.

Table 1
Mean (± CI) subjective ratings of thermal comfort, perceived exertion, movement discomfort and body control at rest, 5 & 20 min, in GYM & GLCS.

Thermal comfort	REST	5 min	20 min
GYM	0	(+)1 (0.63–1.37)*	(+)1.9 (1.30–2.45)
GLCS	0	(+)1.3 (0.76–1.74)*	(+)2.6 (2.27–2.98)*
RPE	**REST**	**5 min**	**20 min**
GYM	6	11.3 (10.7–12.3)*	13 (13.5–12.5)*
GLCS	6	14 (12.7–14.3)*,^	15.4 (14.3–16.7)*,^
Movement Discomfort	**REST**	**5 min**	**20 min**
GYM	**0**	3 (2.17–3.83)*	3.4 (1.94–4.81)
GLCS	**0**	6.3 (5.04–7.46)*,^	7.3 (5.88–8.62)*,^
Body Control	**REST**	**5 min**	**20 min**
GYM	**0**	2 (1.48–2.52)*	2.5 (1.45–3.55)
GLCS	**0**	5.3 (4.36–6.14)*,^	5.8 (4.72–6.78)^

* significant differences with TIME in GYM & GLCS ($p < 0.05$).
^ significant differences across ATTIRE at rest, 5 and 20 min ($p < 0.05$).

in the GLCS only (p=0.09 & p=0.039 respectively). Body control did not change post-5 min.

RPE ($p < 0.016$ & p=0.017) movement discomfort ($p < 0.016$ & p=0.016) and body control (p=0.01 & p=0.011) were greater in the GLCS vs. GYM both at 5 and 20 min respectively, whereas no effect of ATTIRE on thermal comfort was observed.

4. Discussion

This study is the first to determine that donning the GLCS (Mk III) during prolonged moderate (75% VO_2Max) upright cycling is feasible in 1Gz. GLCS-wear augmented initial ventilatory responses and B_L at 20 min which failed to plateau, whereas H_R and T_C continued to progressively increase irrespective of ATTIRE. All subjective ratings except body control continued to increase from 5 min in the GLCS. In addition, GLCS-wear induced exacerbated RPE, movement discomfort and body control from 5 min onwards.

V_E, VO_2, and VCO_2 were greater at 5 min (significant TIME*ATTIRE interactions) suggesting that the early exercise ventilatory response is augmented by GLCS-induced axial loading. This is consistent with initial VO_2 augmentation in studies involving exercise with body armour and cycling whilst wearing the Pengvin Suit [20,21].

Greater initial V_E and VO_2 increments presumably reflect a net increase in work to overcome the resistance to elastic stretch imparted by the GLCS to turn the crank. Such resistance may have induced increased mechanoreceptor afferent feedback that is typically important in determining phase II of the exercise ventilatory response [22], but whose input wains as steady-state (phase III) is achieved. Steady-state exercise is normally achieved within 3 min, though the novelty of induced axial loading may have delayed ventilatory matching. The functional significance of initial ventilatory augmentation is unclear as no difference between ATTIRE was observed at 20 min – when plateau responses indicative of submaximal steady-state exercise [23] were attained. Furthermore, such ventilatory augmentations were not only transient, but of insufficient magnitude to impede sustained performance.

B_L rose disproportionately from VO_2 to be significantly higher in the GLCS at 20 min to levels associated with blood lactate accumulation (OBLA; > mmol L^{-1}) [25]. However, OBLA would be expected for most individuals working at 75% VO_2Max for a prolonged period, even in GYM clothing [9] and is thus unsurprising that B_L remained < 4 mmol L^{-1} in this condition. Nonetheless, there is evidence of B_L accumulation to a greater extent in the GLCS at 20 min, which could be indicative of anaerobic metabolism assumption, though absence of differences in VCO_2 from GYM at this time fails to confirm this. It is however reasonable to assume that if additional load is to be overcome during exercise then anaerobic contribution would not be surprising.

H_R increased from rest and continued to increase between 5 and 20 min in both GYM and GLCS. An absence of differentiation between GLCS and GYM suggests that the circumferential compression imparted by the GLCS (estimated to be ~ 4 mmHg [14] in order to maintain suit-skin friction) has little effect upon systemic cardiovascular regulation. However, whether GLCS-wear affects the modulation of H_R regulation observed in microgravity is unknown. Furthermore, exploration of H_R and other hemodynamic parameters such as cardiac output is warranted in addition to quantification of actual compression, which may vary depending on fluid shifts observed in μG [26].

The imposition of additional axial loading by virtue of the GLCS seemingly has a differential effect upon the H_R and ventilatory response to 75% VO_2Max exercise. Whilst H_R responses were progressively increased, VO_2 was significantly greater only initially, suggesting that the linear relationship between H_R-VO_2 is disrupted. The mechanisms underlying this apparent H_R-VO_2 dissociation in 'altered Gz' remain to be determined, though a ramp protocol up to actual VO_2Max is currently being performed.

H_R witnessed during the final min of exercise was observably lower in the GLCS compared to GYM, hence the tendency for a higher VO_2Max prediction. Such modulations may have significant implications for VO_2Max predictions and exercise countermeasure prescriptions based upon H_R responses. If intensity i.e. power output is based on predicted VO_2Max – as for the ISS – the power needed to maintain 75% VO_2Max would be lower if integrated with this GLCS. However, as previously mentioned, H_R regulation differs in μGz from that in 1Gz. Thus, assessment of cardiorespiratory responses (including VO_2 uptake kinetics) during aerobic exercise in μGz paradigms – such as parabolic flight – is warranted.

Tc continued to rise from 5 min in both GYM and GLCS, which may have increased local skin blood flow to reduce heat load, necessitating progressive H_R acceleration in order to maintain cardiac output [27]. T_C rises were modest however, at no time exceeding 38 °C. Whilst T_C did not differ with ATTIRE, thermal discomfort continued to increase from 5 to 20 min in the GLCS (and GYM). This may be related to the laboratory conditions being less thermo-neutral than deemed, leading to sweat accumulation and thus discomfort [29] although this was much lower than that described for the Pengvin suit [28]. Nevertheless, investigation of repeated wear upon the skin and it skin flora is warranted.

Movement discomfort was unsurprisingly higher in the GLCS, continuing to increase from 5 to 20 min. However levels were moderate and given the fact that subjects donned the GLCS on Earth and thus total Gz was ~1.7Gz [15], values are considerably low. Subjects were naive to wearing the GLCS prior to familiarisation and thus the novelty of additional Gz loading – particularly on the shoulder [30] in addition to apprehension of wearing (and damaging) the GLCS may have contributed to ratings and thus may be lower on subsequent occasions.

RPE was higher in the GLCS from rest, consistent with the perception of having to overcome increased elastic resistance to movement. Studies using elastic resistance have shown increased leg muscle activation compared to when performing traditional resistance exercises i.e. with dumbbells [31] in addition to increased perception of effort. Thus, quantification of the nature, magnitude and co-ordination of neuromuscular recruitment and biomechanics during cycling in the GLCS is warranted to determine possible training effects. Nonetheless, the absence of RPE's > 16 coupled with a lack of back pain reports suggests that prolonged steady-state sub-maximal exercise in the GLCS is achievable in ambient conditions (such as the ISS), in a manner superior to the Pengvin suit (24).

5. Conclusion

The Mk III GLCS induced greater initial exercise ventilatory responses, continual rises in blood lactate and increased perception of workload, but did not impede prolonged submaximal exercise performance. Our novel data suggests that the Mk III GLCS may be a feasible adjunct to exercise countermeasures in space, though determination of actual VO_2Max is warranted due to apparent modulation of the H_R-$\dot{V}O_2$ relationship, and subsequent potential influence on aerobic exercise countermeasure prescription. Future investigations of the GLCS in μGz – involving assessment of loading, hemodynamics and neuromuscular recruitment patterns – during aerobic exercise may help to determine whether the GLCS has promise as a countermeasure to μGz-induced physiological deconditioning.

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